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Opinion paper: How to make our models more physically-based

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Abstract

Catchment-scale hydrological models that are generally called "physically-based" unfortunately only have a partial view of the physical processes at play in hydrology. Although the coupled partial differential equations in these models generally reflect the water balance equations and the flow descriptors at laboratory scale, they miss essential characteristics of what determines the functioning of catchments. The most important active agent in catchments is the ecosystem (and sometimes people). What these agents do is to manipulate the flow domain in a way that it supports the essential functions of survival and productivity: infiltration of water, retention of moisture, mobilization and retention of nutrients, and drainage. Ecosystems do this in the most efficient way, establishing a continuous, ever-evolving feedback loop with the landscape and climatic drivers. In brief, our hydrological system is alive and has a strong capacity to adjust itself to prevailing and changing environmental conditions. Although most physically based models take Newtonian theory at heart, as best they can, what they generally miss is Darwinian theory on how an ecosystem evolves and adjusts its environment to maintain crucial hydrological functions. If this active agent is not reflected in our models, then they miss essential physics.

Through a Darwinian approach, we can determine the root zone storage capacity of ecosystems, as a crucial component of hydrological models, determining the partitioning of fluxes and the conservation of moisture to bridge periods of drought (Gao et al., 2014a).

Another crucial element of physical systems is the evolution of drainage patterns, both on and below the surface. On the surface, such patterns facilitate infiltration or surface drainage with minimal erosion; in the unsaturated zone, patterns facilitate efficient replenishment of moisture deficits and preferential drainage when there is excess moisture; in the groundwater, patterns facilitate the efficient and gradual drainage of groundwater, resulting in linear reservoir recession. Models that do not account for these patterns are not physical. The parameters in the equations may be adjusted to compensate for the lack of patterns, but this involves scale-dependent calibration.

In contrast to what is widely believed, relatively simple conceptual models can accommodate these physical processes very efficiently. Of course the parameters of catchment-scale conceptual models, even if they represent physical parameters, such a time scales, thresholds and reservoir sizes, require calibration or estimation on the basis of observations. Fortunately, we see the emergence of new observation systems from space that become more and more accurate and detailed as we go along. Recent products estimating precipitation and evaporation from space have shown to allow the estimation of the root zone storage capacity of ecosystems globally (Lan-Erlandsson et al., 2016), DEMs allow the identification of heterogeneity in the landscape, providing information on the heterogeneity of dominant runoff generating mechanisms (Gharari et al., 2011, Gao et al., 2014b), and gravity observations from space can be used to estimate sub-surface storage fluctuation and groundwater recession (Winsemius et al., 2009). As a result, it will become more and more practical to calibrate well-structured conceptual models, even in poorly gauged catchments. These insights and developments will contribute to the revaluation of conceptual models as physics-based representations of hydrological systems.

1. Introduction

“The whole is greater than the sum of the parts” and “Everything changes and nothing remains still […]” are quotes commonly attributed to the Greek philosophers Aristotle (384-322 BC) and Heraclitus (535-475 BC). More recently, but still before Darwin developed his theory on evolution, Alexander von Humboldt (1769-1859) considered nature and its processes as an inseparable entity, where all forces of nature are connected (Wulf, 2015). Although these concepts were not formulated specifically to describe the movement of water through the natural environment, they very pointedly summarize what controls hydrological functioning at the catchment scale.

Ironically, state-of-the-art so-called "physically based" catchment-scale hydrological models do an astonishingly poor job in addressing the above system characterizations in a meaningful and consistent way, albeit for different reasons, depending on the model under consideration. This inevitably results in models being inadequate representations of real-world systems, haunted by frequently unreasonable model and/or parameter uncertainties and thus unreliable predictions.

There has now for several decades been an ongoing controversy about the individual benefits and flaws of top-down (i.e. conceptual) versus bottom-up (i.e. physically-based) modelling strategies. Beven (1989), for instance, stated that the so-called "physically-based" models fail to use a proper theory of up-scaling, cannot deal adequately with heterogeneity, and suffer from the curse of dimensionality and the sheer impossibility of parameter calibration. Without doubt, this is an important and well-justified discussion as it helps to improve different aspects of current modelling practice. Yet, it almost completely ignores that a significant

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proportion of uncertainty in current-generation catchment-scale hydrological models -- both conceptual and physically based -- can be directly linked to the fact that our conceptual understanding of two of the critical aspects of the system, as encapsulated in the above two quotes, is only insufficiently or often not at all accounted for in these models. Rather, much of the discussion concentrates on data uncertainty and availability.

This rightfully emphasizes our problem to meaningfully test and constrain models in the absence of reliable observations at the scale of interest and the resulting unwanted effects of equifinality, but does largely not question the validity of model concepts themselves. For example, a frequently expressed criticism of conceptual models is still that they are ad hoc and poorly testable empirical formulations that are not explicitly based on first principles and always require calibration. Indeed, the parameters in these models do require some way of calibration, but that does not mean that the parameters do not represent physical quantities if used at the right scale and for the correct processes. Physically based models suffer from the same shortcomings. With observations at the spatial scales and resolutions of the model domain not being available, parameters of physically based models cannot be independently determined either. And what is wrong with empirical formulations? Does empirical research not imply the derivation of natural laws based on observations, in the same way as for example Darcy’s law was originally derived? But what is really wrong with our models is that they insufficiently or even not at all reflect both, internal organization of the system as well as the capacity of the ecosystem living on the substrate to manipulate the system in response to the temporal dynamics of the boundary conditions.

1.1. The whole is greater than the sum of the parts

Observations from a wide range of natural systems strongly suggest that whenever one medium flows through another medium as a result of a gradient, patterns appear (Savenije, 2009). Examples include surface water flowing over the landscape or groundwater seeping out of a beach on the lowering tide, both forming drainage and erosion patterns. A clear analogy with drainage patterns is water flowing through a leaf or blood flowing through a body in a system of veins. But there are also examples from places afar, such as ice melting on Mars forming similar drainage patterns as in landscapes on Earth. Most conceptual models implicitly account for such structures by the use of modelling components that represent some sort of preferential flow paths and which are controlled by calibrated parameters, effective at the modelling scale. These parameters, on the one hand, typically represent the integrated, effective hydraulic conductivity over the model domain. On the other hand, they characterize spatial distribution functions that describe connectivity patterns of these flow paths in a spatially heterogeneous domain. In contrast, most physically-based models do not account for emergence of patterns and self-organization. Notwithstanding a handful recent developments that use conceptual formulations based on dual- or multi-domain flow, most physically-based models are rather based on simple and straightforward aggregation of processes from the lab-scale to the catchment scale, assuming that there is no structure and organization in the system as the modelling scale increases from the grid scale to the full domain of the model application. Thus, according to these models, the only place in nature where there are no drainage patterns is in the subsurface, i.e. in the root zone, in the unsaturated zone below it, and in the groundwater. This is conceptually wrong, because subsurface drainage patterns, manifest as preferential flow paths and created by diverse biological, physical and chemical processes, do appear at a wide range of spatial and temporal scales. Examples include animal burrows (e.g. earth worms; Zehe and Flühler, 2001; Schaik et al., 2014), former root channels, soil cracks, rock interfaces, and fissures, which are further reinforced by internal chemical and physical erosion processes. Typically characterized by convergent flow, reduced flow resistance and higher flow velocities, these patterns, as manifestations of structure and organization, provide efficient drainage as well as transport capacity for dissolved or suspended substances.

1.2. Everything changes and nothing remains still

But there is more to it. Our hydrological system is not just a dead configuration of earth material through which water flows. It is the foundation of living ecosystems, which manipulate the environment in such a way that it can survive and reproduce efficiently. Ecosystems clearly do not do this in a conscious way with an objective in mind. Rather, the mere fact that they have survived is proof that they have done so efficiently and that their current state is a manifestation of their individual developments in the past. The trajectory and not the current structure control the system response. This is Darwinian thinking, alien to the purely mechanistic, Newtonian philosophy on which much of our state-of-the-art modelling concepts are based.

Hydrological systems at all spatial scales, from the plot to the catchment scale, rather need to be understood as meta-organisms (e.g. Bosch and Miller, 2016), i.e. systems of living biological entities, that occupy an ecological niche and that interact mutually but also with their inanimate environment. As such, it is needless to mention that the current appearance and characteristic of these systems is clearly not the endpoint of their trajectories and that they keep on to continuously and dynamically evolve over a wide range of temporal scales! Yet, current generation models are mostly built on the foundations of time-invariant system boundary conditions. This is strongly reflected, for example, in parameter selection/calibration procedures that integrate out the effects of a system continuously adapting to its environment over time. This modelling strategy therefore provides us with system characterizations that are only snapshots in time and that deprive us of developing a better understanding of what drives the change and thus of the systems' future trajectories.

2. The crucial elements of a hydrological model

Any hydrological model that claims to be physical has to properly reflect key elements of hydrological systems. The first key element is the proper reflection of the partitioning points that the ecosystem creates to optimise system functions: infiltration, retention, and drainage. The second key element is that in the landscape patterns emerge, on and below the surface, that facilitate efficient ways of drainage and infiltration.

2.1. Representation of partitioning points

In a hydrological system we can identify two major partitioning zones controlling how and where precipitation is partitioned into different upward, downward or lateral fluxes. The first partitioning zone is located at the (near-) land surface, where precipitation is split into (1) direct feedback to the atmosphere from canopy interception, ground interception, and open water (2) infiltration into the root zone and (3) surface runoff (Hortonian infiltration excess overland flow and Dunne saturation excess overland flow). Water infiltrating into the soil eventually reaches the second partitioning zone, the root zone, which splits the incoming moisture into (4) transpiration by vegetation, (5) soil evaporation, (6) subsurface saturation and/or infiltration excess flow, e.g. the fill-and-spill theory and/or rapid sub-surface flow

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through preferential drainage structures within and below the root zone and (7) percolation to the groundwater.

If one wants to describe the hydrological functioning of a hydrological unit or catchment, an accurate description critically hinges on a meaningful definition of this partitioning and the residence times of the moisture in the two system partitioning zones. What characterizes and shapes these two partitioning zones and thereby controls their respective functioning, are largely the biotic components of the ecosystem, i.e. vegetation, animals and microorganisms, living in a given landscape. In fact, the ecosystem actively adjusts to manipulate water fluxes and residence times in a way that the landscape provides the right functions to increase the ecosystems (or individual components thereof) chance of survival. These functions are (1) facilitating infiltration so as to efficiently recharge root zone soil moisture and to optimise subsurface drainage (2) retention of sufficient moisture for vegetation to overcome critical periods of drought, (3) efficient drainage of excess water, to ensure sufficient oxygen supply for roots and (4) maintenance of a healthy substrate with an adequate availability of nutrients. The latter implies the prevention of excessive erosion and leaching of valuable nutrients. If, and only if vegetation manages to develop in a way that allows to sufficiently satisfy all these functions, it will manage long-term survival. Otherwise, due to an excessive allocation of scarce resources for the growth and maintenance of a suitable root system, insufficient resources for surface growth will be available. As a consequence, a given species will experience a disadvantage in the competition with species that are more adapted to the environmental conditions at a given location. They will eventually be replaced by the better adapted species, changing the dynamics and pattern not only of the plant community at that location but also affecting the entire ecosystem around it and thereby its influence on the hydrological functioning. These changes can include for example changes to the root system, the canopy or the animal and microorganism communities in the area. All of which can result in changes to the pathways of water (and nutrients) through the system and eventually affect how the system stores and releases water and nutrients.

There is increasing experimental (e.g. Brooks et al., 2010; Evaristo et al., 2015) and theoretical evidence (e.g. Hrachowitz et al., 2013; Van der Velde et al., 2015) for such an eco-hydrologically controlled partitioning that regulates the contrasting requirements of storage and drainage of water and nutrients, which has recently been comprehensively summarized in the two-water-worlds hypothesis (McDonnell, 2014; Good et al., 2015).

Briefly, root systems extract water and nutrients mainly from the soil matrix, which is characterized by relatively small pore sizes. The high specific surface areas of these small pores provide a high water and nutrient adsorption capacity. The resulting flow resistances reduce the flow velocities and create zones that drain, depending on the moisture content, at very low rates, as reflected in the concept of field capacity. This in turn provides efficient moisture storage buffers in this part of the soil. The elevated negative hydraulic potential (i.e. high suction forces) in the soil matrix during and at the end of dry periods, caused by the gradual extraction of water by roots for plant transpiration, then results in incoming, new water to be tightly adsorbed in the pores of the matrix to replenish the buffer. In contrast, larger pores, having lower specific surfaces and thus less adsorption capacity only start to fill with increasing moisture content of the soil, when the small pores are increasingly saturated. The lower flow resistances in these larger subsurface features provide less buffer but rather allow for higher flow velocities. They thereby provide an efficient mechanism for water to bypass the soil matrix with little interaction and to drain excess water through a network of preferential channels when the system is in a wet state. Although not independent of each other, water stored in the matrix for transpiration and water in preferential features, generating stream flow, is therefore characterized by distinct age signatures, effectively constituting distinct pools of water, i.e. eco-hydrological separation. This system with a continuous distribution of pore sizes over a wide range of scales, has evolved from the co-evolution of climate and hydrology with the ecosystem in a Darwinian process (e.g. Sivapalan et al., 2011; Blöschl et al., 2013). Being in a dynamic equilibrium, the state of such a system at any given time is a manifestation of its past trajectory and reflects the conditions for survival at that time.

2.2. The emergence of patterns and their properties

Implicit in the domain-integrated descriptions of the system in model applications with little spatial discretization, i.e. mostly lumped or semi-distributed conceptual models, but what many "physically based" models do not see, is that there is an underlying process of maximum efficiency that underlies the principle of self-organisation. The Earth system is continuously receiving solar energy. This energy needs to be dissipated in an efficient way to produce entropy (e.g, Michaelian, 2012). According to Kleidon (2016), the process of energy conversion corresponds with maximum power or maximum entropy production, close to the Carnot limit, leading to the evolution of patterns of efficient transport of erosion products. Eventually this self-reinforcing mechanism, i.e. positive feedback loop, creates an organised system of drainage (Kleidon et al., 2013).

As argued by Dooge (1986), catchments are "complex systems with some degree of organisation"; in other words, it is "organised complexity" (Dooge, 2005). This organisation is dominated by the ecosystem, which is not static but rather alive and continuously evolving. Given the strong evidence for the interactions between hydrological functioning, climate and ecosystem (e.g. Milly, 1994; Rodriguez-Iturbe and Porporato, 2007; Alila et al., 2009; Gao et al., 2014a), it is inconceivable that the hydrological system remains unaltered under climate or land-use change. It is rather adjusting in response to changing environmental conditions and thereby actively and continuously adjusting the partitioning zones at a wide range of spatial and temporal scales. The dominant ecosystem that emerges will in a Darwinian sense then tend to maximum efficiency for survival.

The ecosystem shapes the hydrological system in a way that it converges towards a dynamic equilibrium between infiltration, retention, drainage and prevention of erosion, thereby creating conditions favourable for its own survival. In a feedback, hydrology on its own term then similarly shapes the ecosystem. If we want to model such systems, we have to realise that our models need to reflect this dynamic and continuous feedback loop. In other words, our models need to be organic and alive, just as natural systems are. No need to try and describe the sub-surface partitioning zone, i.e. the root zone, in multiple layers with different properties and detailed estimates of root depths. Such data is rarely available at the level of required detail anyway and if it is available, it was mostly obtained from one-time sampling campaigns with no information about their respective temporal trajectories.

Consider, as a thought experiment, the case of a plant species in a humid climate at a location with a relatively poorly drained soil such as loam. From experiments with individual plants of that species an estimate of average root depth at that location can be obtained. Together with estimates of soil porosity, the water storage capacity in the root zone of that location can be readily determined. This, however, ignores on the one hand that root systems can and do adapt to variability in environmental conditions at time scales relevant for hydrological applications. On the other hand, posing that plants from the same species have common limits of operation, such as water and nutrient requirements, and following from the arguments above, it is implausible to use the above root depth estimates for the same plant that grows in a drier climate and/or at a different location with well-drained, coarser soils, such as sand. The estimated storage capacity will be considerably underestimated and will merely reflect the differences in soil properties. However, if the same species survived in a different climate or on that different soil, this implies that it had sufficient access to water and nutrients. In other words, the plant developed a different, i.e. deeper and/or denser, root system that could ensure access to the same volume of water as in the first location (cf. Gao et al., 2014a; DeBoer-Euser et al., 2016). Thus, the ecosystem controls the hydrological functioning of the root zone in a way that continuously optimizes the functions of infiltration, moisture retention, drainage and prevention of erosion.

The result of such a co-evolution between climate, ecosystem, substrate and hydrological functioning typically exhibits surprisingly simple patterns given the complex and highly heterogeneous combination of soils, geology, topography and climate and their mutual interactions. Thus, even relatively simple lumped or semi-distributed conceptual models have in the past shown considerable skill in describing that and in reproducing hydrological functioning in a wide variety of landscapes and climates. In fact, it is highly likely that the these models' relatively simple closure relations that are based on integrated and simple descriptions of the system, such as linear reservoirs for the groundwater, spatial distribution functions to characterize the impact of spatial heterogeneity on connectivity and storm flow generation or functions representing the catchment-integrated relationship between energy input, soil moisture and transpiration are manifestations of energetic optimality, most likely at a state of maximum power (e.g. Kleidon, 2016).

Apparently, ecosystems are capable of creating resilience against variability by which they create predictable behaviour within a complex environment; otherwise it could not have survived. Upscaling from the lab-scale to the landscape scale is wrong if the ecosystem is not included as an active agent creating resilience against the variability of nature.

3. Why conceptual models are suitable tools to represent these hydrological properties

Several hydrologists have remarked on the paradox that instead of more complexity, simplicity emerges in catchment behaviour as more processes come into play (e.g. Sivapalan 2003a). This happens at a scale where the hydrological unit has sufficient size to achieve a certain level of organisation. Self-organisation leads to less complexity (Dooge, 2005). Conceptual models, being a configuration of relatively simple relationships, seem therefore more adequate to deal with systems that have reached some degree of organisation. But it is not merely the simplicity.

Let us consider a conceptual model that consists of three main stores that correspond with the three partitioning points: the surface reservoir, the root zone reservoir and the groundwater reservoir. The surface reservoir represents the retention of moisture by canopy and ground interception, which has a relatively small storage capacity from which the moisture can evaporate directly back to the atmosphere. Above the capacity threshold the moisture is split into infiltration and surface runoff, depending on a threshold defined by the infiltration capacity. There is nothing non-physical about this. The key lies in the infiltration function, but this is not particular for conceptual models.

The root zone storage in a conceptual model can be brought in tune with the storage requirement of the vegetation. This can be derived in a Darwinian sense and can lead to scale-independent estimates of root zone storage capacity for given ecosystems (Gao et al., 2014a; Wang-Erlandsson, 2016). This is a fully physical storage capacity. When the store is full, sub-surface runoff and recharge is generated. At aggregate scale, there is spatial heterogeneity in the ecosystems, which leads to a probability distribution of the threshold above which runoff is generated. This can, for example be done by a Beta distribution (or any other suitable distribution), such as in the Xinangjiang (Zhao & Liu, 1995) or VIC model for storage or saturation excess runoff. If the runoff mechanism is sub-surface flow, then the threshold is sub-surface saturation above a less permeable layer; if the mechanism is saturation excess overland flow, then it describes the increasing saturated area of a catchment (Dunne & Black, 1970). Again, this is purely physical, as long as the right runoff mechanism is applied to the appropriate landscape: sub-surface flow on hillslopes and Dunne overland flow on landscapes where groundwater can reach the surface (wetlands and riparian zones). The rooting of the flow toward the stream network can be done by simple transfer functions, linear reservoirs or cascades. This is just a matter of routing and does not affect the partitioning or the water balance.

Finally, data from catchments worldwide suggest that groundwater systems at the catchment-scale work in many cases as linear reservoirs in natural catchments. This agrees with the frequently observed exponential recession of river flow during rainless periods. Why the dynamic part of the groundwater is organised in this simple way is still one of the fundamental questions in hydrology, but the answer is likely to be found in the theory of maximum power or maximum entropy production. Whether or not the answer to this question will be found sooner or later does not affect the viewpoint that the exponential depletion of

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groundwater is physical and real. The linear reservoir is not more or less physical than Darcy's equation.

Conceptual models are quite capable of representing these processes in a simple and adequate way, provided we account for landscape ecosystem and land cover. If there is considerable heterogeneity in the climatic drivers (precipitation and energy), or if these drivers are available at grid-scale, then the stocks of the conceptual models can be distributed spatially, so as to account for the spatial heterogeneity of the moisture states. Conceptual models do not have to be lumped, as long as the system descriptors reflect the processes at the hydrological unit scale at which they emerge.

4. So what are the practical consequences?

Ironically, this implies that bringing in more physics -- i.e. the right kind of physics -- into our models makes them simpler. Apparently, simplicity -- that is to say the right kind of simplicity -- enhances the physics of our hydrological models. Rather, if a model is too complex, then that may be an indication of a lack of physics, or of the wrong application of physics. This is good news for prediction in ungauged basins. As was implied by Sivapalan et al. (2003b), our limited ability to predict hydrological behaviour in ungauged basins is an indication of our lack of understanding of essential physical processes. In fact, it was this inability that was the main trigger for the PUB science decade (2003-2012), which aimed at enhancing our understanding of physical processes as much as our capacity to predict under circumstances of data scarcity.

We have now come a long way to prediction in ungauged basins (Blöschl et al., 2013). With the emergence of new tools, mostly based on observations from space, we can do a lot more, and at a scale where self-organisation is present, that is the first order catchment, which already, or in the near future, is the scale at which we can observe hydrological characteristics from space. We claim that with the present tools (DEMs, remote sensing-based products to estimate evaporation and precipitation, and gravity observations from space) we can get very far, and will definitely be able to do so with much more certainty as these tools become more and more accurate (see Figure 1)[1]. In the following we summarise four essential characteristics and parameters that we can derive with these tools.

4.1 Landscape classification on the basis of DEMs

Different landscapes may be characterized by different dominant hydrological processes. Topographical indicators such as: slope, HAND (Height Above the Nearest Drainage, according to Rennó et al. (2008)), aspect, elevation or TWI (topographic wetness index; Beven and Kirkby, 1979) have in the past shown considerable potential to quantify the heterogeneity of landscapes. In a recent example Savenije (2010) suggested a classification into three landscape elements: wetlands and riparian zones, where the dominant mechanism is saturation excess overland flow; hillslopes, where the dominant mechanism is storage excess sub-surface flow; and plateaus and terraces, where the dominant processes are deep percolation and infiltration excess (Hortonian) overland flow. Gao et al. (2014b) identified additional observable landscape elements: rocky mountains/bare rock, glaciers as well as grass and forest hillslopes. Figure 2 presents an illustration of a conceptual model based on three landscape elements: plateau, hillslope and wetland. These landscape elements operate in parallel but are connected through the groundwater system, which is fed from plateau and

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[1] This and the following figures are taken from the poster presented at the symposium in honour of Eric Wood (Princeton, 3 June 2016) attached in supplement

hillslope and which sustains the shallow groundwater in the wetland through an upward flux. As was recently shown (e.g. Gao et al., 2014b; Gharari et al., 2011, 2014; Hrachowitz et al., 2014) such more complex conceptual models, paradoxically, are easier to calibrate and have less predictive uncertainty than lumped models (even if the moisture is accounted in a distributed way), because the dominant processes are not lumped, but modelled separately according to the landscape proportions associated with these processes.

4.2 The root zone storage capacity derived from E and P products

Recent work has shown that the catchment-scale moisture retention capacity in the root zone can be estimated based on a Darwinian theory. If an ecosystem has been able to survive some critical periods of drought, where the evaporation E is larger than the precipitation P, then apparently it had sufficient storage to overcome this drought. By simulation of past P and E values, this storage capacity that apparently was there can be evaluated and treated statistically. Wang-Erlandsson et al. (2016) found that different ecosystems apparently tune to a different drought return period in agreement with their survival strategy. Grasslands, for instance, tune to an average drought (with a return period of 2 years) because grass goes dormant during severe droughts. But evergreen forest appears to tune to much longer return periods of about 60 years, which is long enough to make sure the species survive. Figure 3 presents the global picture of these root zone storage capacities. Other researchers (Gao et al., 2014a; De Boer-Euser et al., 2016) also used this approach making use of E estimates based on long term water balances, and showed that the obtained root zone storage capacities are accurate and at least as good as methods deriving them in traditional ways. With this method, the root zone storage capacity of each landscape element can in principle be determined, at any scale where information on E and P is available.

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4.3 Groundwater recession from gravity observations

Another parameter that can be estimated independently from space is the groundwater recession time scale, which is the same as the time scale of the flow recession curve when the river is fed by groundwater. For details, reference is made to the attached poster, but the essence is that the root zone and the groundwater system are disconnected during dry periods (e.g.: Brooks et al., 2010; McDonnell, 2014). If we dispose of gravity time series from space (i.e. GRACE; e.g. Winsemius et al., 2006), we have estimates for the total water equivalent storage, *W*, which is the sum of all water stores (surface, unsaturated and saturated zone). During the dry season, when there is a disconnect between the (sub-)surface and the groundwater, the temporal gradient of the surface and sub-surface stores can be replaced by (*P-E*). If we subtract (*P-E*) from the temporal gradient of *W* (d*W*/d*t*), we thus obtain the recession of the groundwater storage S_g (dS_g/dt, see Figure 4). The temporal recession of S_g, obeys the same exponential function as the recession in the drainage network during recession, acting as a linear reservoir, implying that the time scale of the recession K_s thus obtained reflects the recession parameter of the conceptual model.

4.4 Can we predict runoff without ground stations? [2]

Thus already with the present remote sensing-based tools, we can derive crucial hydrological parameters from independent data sources (for parameter definitions, see Figure 2): the root zone storage capacity $S_{u,max}$ for different vegetation classes from *E* and *P* products; and the recession time scale K_s from gravity observations from space. If subsequently we estimate interception capacities S_i from land cover information, which can be done with reasonable accuracy, then there are only few parameters left to calibrate, such as the exponent β of the

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[2] see attached poster in Supplement, presented at the symposium in honour of Eric Wood (Princeton 3 June 2016)

spatial distribution function, the splitter D of preferential recharge, and the fast recession time scales K_f. Because in the above we have not yet simulated the entire time series, what one could do next is to drive the conceptual model with P and calibrate on the time series of E and W (e.g. Winsemius et al., 2009). This would allow estimation of the remaining three parameters.

At the present level of technology there is still considerable uncertainty in the estimation of E, P and W time series. But these products are getting better by the day. On top of that, we have more and more access to accurate altimetry, which could in the future allow calibration on water levels, making use of hydraulic equations. Already now, calibration on lake levels is possible, and a few studies even already ventured in using altimetry for the determination of accurate river geometry, river levels and, using hydraulic equations, validation and even calibration of runoff on water levels (e.g. Sun et al., 2012, 2015).

5. Conclusions

As hydrological scientists, we would like all our models to be "physically-based". On this issue we do not disagree. What we sometimes disagree about, is what type of physics we need to include. In this opinion paper, we argue that if a model does not contain the characteristics of an active organising agent, i.e. the ecosystem, then the model cannot claim to be physical. This active agent has organised moisture retention, infiltration and preferential drainage. Conceptual models are very well capable of representing these functions. On top of that, over millennia, the groundwater system has organised its drainage according to the most efficient way of dissipating energy (e.g. Kleidon, 2016). The linear reservoir behaviour of groundwater at catchment scale is a manifestation of that. The linear reservoir is a simple and straightforward way of modelling groundwater, much more direct and simple, and paradoxically more correct, than using a three-dimensional model that up-scales the Darcy equation.

If we realise that our physical system is organised, following some form of optimality, whether we call it maximum entropy production or maximum power, then our hydrological world becomes more simple and even more predictable. In recent years, the focus on small-scale physics and the believe in the ever-increasing computer power, have prevented us from developing holistic modelling strategies that provide more plausible descriptions of how nature really works at the macro scale (e.g. Savenije, 2001).

The good news is that these holistic approaches match very well with the newly arising remote sensing-based tools that are increasingly getting better. The chances are not remote that the global ambition of the PUB decade to predict runoff in ungauged basins at acceptable levels of certainty, will be reached in the not too distant future. This is of course, provided we use the right physics.

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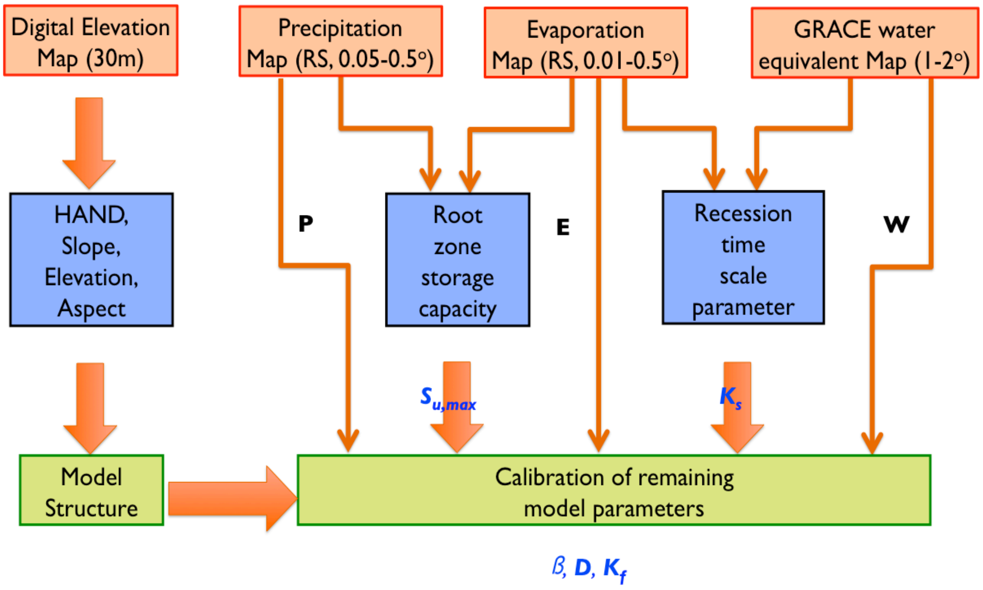

Figure 1. Flow diagram for Prediction in Ungauged Basins

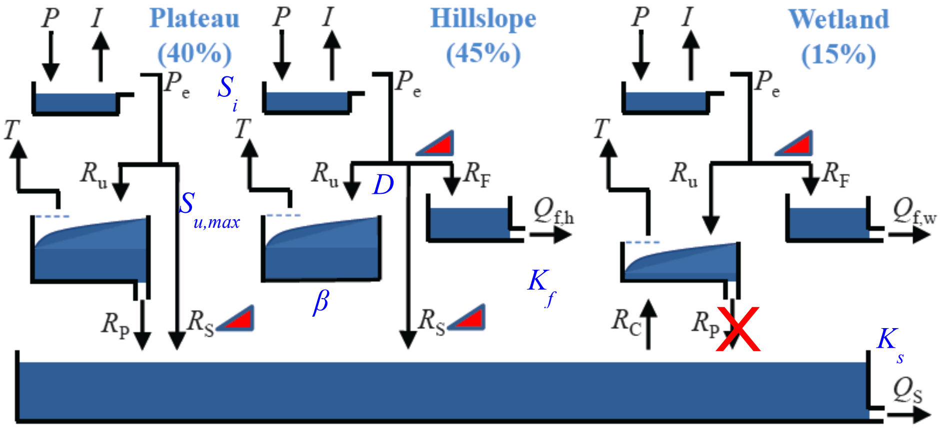

Figure 2. Model structure derived from DEM, showing three landscape classes and the groundwater system connecting them.

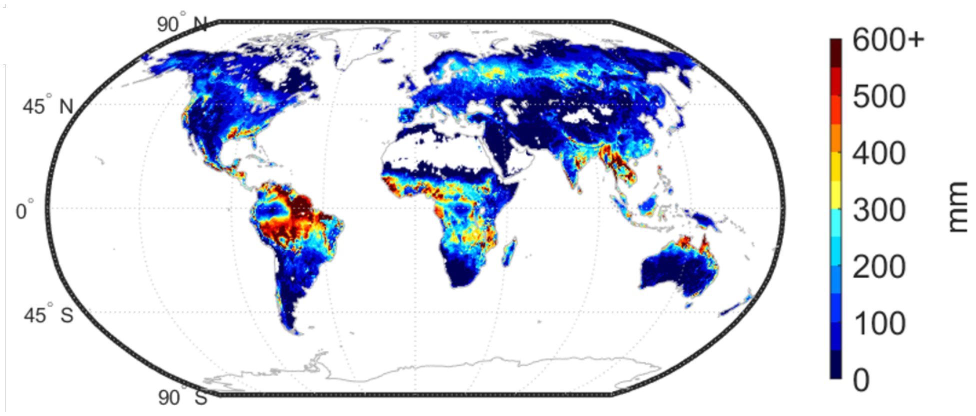

Figure 3. Root zone storage capacity as determined by Wang Erlandsson et al. (2016)

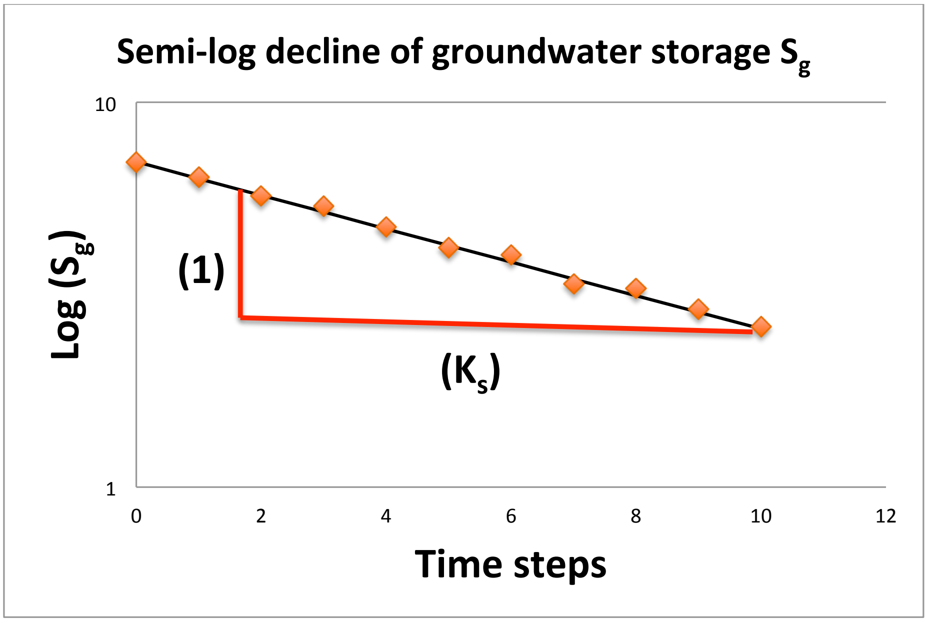

Figure 4. Indication of how groundwater recession can be determined by gravity observations from space.